DISTINCTIVE CHARACTERISTICS OF THE PARTICLE-SIZE DISTRIBUTION OF TYPICAL SOLONCHAKS DEVELOPED ON THE DRIED ARAL SEA BED

S. Makhammadiev[1], T. Abdrakhmanov[2], Dj. Sattarov[3], Z. Jabbarov[4], Sh. Abdullaev[5], O. Imomov[6], U. Nomozov[7]

National University of Uzbekistan named after Mirzo Ulugbek, Associate professor of the Department of Soil Science, docent, Faculty of biology and ecology[1]

National University of Uzbekistan named after Mirzo Ulugbek, Professor of the Department of Soil Science, Faculty of biology and ecology[2]

National University of Uzbekistan named after Mirzo Ulugbek, Professor of the Department of Soil Science, Faculty of biology and ecology[3]

National University of Uzbekistan named after Mirzo Ulugbek, Professor of the Department of Soil Science, Faculty of biology and ecology[4]

National University of Uzbekistan named after Mirzo Ulugbek, Teacher of the Department of Soil Science, Faculty of biology and ecology, teacher[5]

National University of Uzbekistan named after Mirzo Ulugbek, Department of Soil Science of the Faculty of biology and ecology, doctarate[6]

Tashkent branch of Samarkand State Veterinary Medicine, University of livestock and biotechnology, teacher[7]

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Abstract. *The desiccation of the Aral Sea has resulted in the formation of extensive areas of newly exposed land characterized by severe environmental degradation, salinization, and aeolian erosion. Understanding the physical properties of soils developing on the dried seabed is essential for assessing their ecological condition and restoration potential. This study aimed to investigate the granulometric composition and profile distribution of particle-size fractions in typical solonchaks formed on the dried bottom of the Aral Sea and to evaluate their pedological and ecological significance. Field investigations and laboratory analyses were conducted on a representative soil profile. The particle-size distribution was determined using standard soil mechanical analysis methods. The results revealed considerable vertical variability in soil texture throughout the profile. The upper horizons (0–27 cm) were dominated by sandy fractions, particularly coarse and fine sand particles, indicating the strong influence of marine sediments and subsequent aeolian reworking processes. In the surface layer (0–0.5 cm), coarse sand (>0.25 mm) accounted for 63.0% of the soil mass, while physical clay content was only 12.4%, classifying the horizon as sandy loam. In contrast, subsurface horizons exhibited increased proportions of fine particles, with physical clay content reaching 35.0% at depths of 27–48 cm, corresponding to a medium-loam texture. The observed textural differentiation reflects the combined effects of marine sedimentation, sea regression, and wind-driven redistribution of sediments. Sandy surface horizons are characterized by high infiltration rates, low water-holding capacity, weak structural stability, and high susceptibility to wind erosion. Conversely, loamy subsurface layers possess improved moisture retention, higher cation exchange capacity, and greater potential for salt accumulation. These characteristics significantly influence soil hydro-physical properties, salinity*

dynamics, vegetation establishment, and ecological resilience. The findings indicate that granulometric composition is a key factor controlling soil development and ecosystem recovery on the dried Aral Sea bed. The predominance of sandy materials in surface horizons highlights the necessity of implementing phytomeliorative measures using drought- and salt-tolerant species to reduce deflation and promote ecological stabilization. The results provide a scientific basis for sustainable land management and restoration strategies in the Aralkum Desert.

Keywords: *dried seabed, Aral Sea, solonchaks, granulometric composition, soil texture, physical clay, salinity, aeolian processes, phytomelioration, Aralkum Desert.*

1. Introduction

The desiccation of the Aral Sea is recognized as one of the most severe anthropogenic environmental disasters of the twentieth century, resulting in profound ecological, hydrological, and pedological transformations across Central Asia. Since the 1960s, intensive diversion of water from the Amu Darya and Syr Darya rivers for irrigation purposes has caused a dramatic decline in the Aral Sea's water level, exposing more than 6 million hectares of former seabed. This newly emerged landscape, commonly referred to as the Aralkum Desert, has become a unique natural laboratory for studying primary soil formation, salinization processes, and ecosystem succession under extreme arid conditions (Micklin, 2007; Zonn et al., 2009). Recent studies have emphasized that soils developing on the dried Aral Sea bed represent a complex combination of marine sediments and aeolian deposits, resulting in highly heterogeneous physical and chemical properties (Issanova et al., 2015). Due to their relatively young age and dynamic formation processes, these soils exhibit significant variability in granulometric composition, salinity distribution, and biological activity. Understanding the mechanical composition of these soils is therefore essential for assessing their ecological stability and reclamation potential. Soil texture is widely recognized as one of the most fundamental properties controlling soil formation, water movement, nutrient dynamics, and ecosystem functioning. According to Brady and Weil (2017), the proportions of sand, silt, and clay fractions largely determine soil hydraulic conductivity, water retention capacity, aeration status, aggregate stability, and nutrient availability. In arid and semi-arid regions, where water is the primary limiting factor, soil texture plays an especially important role in regulating vegetation establishment and ecosystem resilience (Hillel, 2004). Numerous investigations conducted in the Aral Sea region have reported a predominance of sandy and sandy-loam materials within recently exposed seabed areas. Bortnik and Chistyaeva (2010) noted that the upper layers of the dried seabed are largely composed of coarse and fine sand fractions derived from marine sediments and subsequently modified by wind erosion processes. The dominance of sandy particles contributes to rapid infiltration rates but low water-holding capacity, creating unfavorable conditions for plant growth and accelerating desertification processes. The relationship between soil texture and salinization has been extensively documented in saline environments worldwide. Richards (1954) first demonstrated that fine-textured soils tend to accumulate larger amounts of soluble salts due to their higher specific surface area and capillary rise potential. Similarly, Abrol et al. (1988) reported that clay-rich horizons generally exhibit greater cation exchange capacity (CEC), facilitating the accumulation of sodium ions and enhancing sodification processes. Consequently, the distribution of clay particles within the soil profile strongly influences salinity dynamics and reclamation efficiency. Research conducted in the Aral Sea basin has shown that physical clay content is positively correlated with the accumulation of soluble salts and exchangeable sodium. Safarov et al. (2021) observed that

horizons containing higher percentages of clay and fine silt fractions exhibited significantly greater electrical conductivity values compared to sandy layers. These findings indicate that mechanical composition serves as an important predictor of salinity distribution patterns in the dried seabed soils. In addition to salinization, soil texture significantly affects susceptibility to aeolian erosion. The newly exposed Aralkum surface has become one of the world's largest sources of salt-dust emissions. According to Groll et al. (2016), between 80 and 100 million tons of salt and dust particles are transported annually from the dried Aral Sea bed. These aerosols consist primarily of fine sand, silt, and salt particles that can be transported over hundreds or even thousands of kilometers, negatively affecting agricultural productivity, human health, and regional climate conditions. Aeolian processes play a dual role in soil development within the Aralkum region. On the one hand, wind erosion removes fine particles and organic matter from the soil surface, thereby accelerating degradation. On the other hand, aeolian deposition contributes to the formation of new sedimentary layers and influences the vertical differentiation of soil profiles (Issanova et al., 2015). Consequently, the current granulometric composition of Aralkum soils reflects the combined influence of marine sedimentation and long-term wind redistribution processes. The ecological consequences of soil texture heterogeneity are also reflected in vegetation succession patterns. Dimeyeva and Breckle (2015) demonstrated that plant colonization on the dried seabed is strongly controlled by soil mechanical composition. Sandy and sandy-loam substrates provide favorable conditions for the establishment of psammophytic species, whereas finer-textured soils support a broader range of halophytic vegetation. These differences significantly influence ecosystem development and soil stabilization processes. Among the most important pioneer species utilized for ecological restoration are Haloxylon aphyllum, Calligonum spp., and Salsola richteri. These drought- and salt-tolerant plants possess extensive root systems capable of stabilizing loose sediments, reducing wind erosion, and enhancing organic matter accumulation (Dimeyeva et al., 2018). Their successful establishment is largely dependent on the physical properties of the substrate, particularly soil texture and moisture retention capacity. Recent studies have increasingly focused on phytomelioration as a sustainable strategy for restoring degraded lands within the Aral Sea region. Research indicates that vegetation cover can significantly reduce dust emissions, improve soil structure, and promote biological activity (Li et al., 2022). The effectiveness of phytomeliorative measures, however, varies according to soil texture, salinity level, and groundwater conditions. Another important aspect receiving growing scientific attention is the role of soil texture in carbon sequestration and climate change mitigation. Lal (2020) emphasized that fine-textured soils generally possess a greater capacity for long-term stabilization of soil organic carbon due to enhanced organo-mineral interactions. Consequently, the loamy horizons identified within Aralkum soils may represent potential sites for carbon accumulation following successful vegetation restoration. Recent advances in soil restoration technologies have highlighted the benefits of organic amendments such as compost, manure, and biochar. Lehmann and Joseph (2015) demonstrated that biochar application improves aggregate stability, increases water retention, and enhances microbial activity in sandy soils. Similar approaches are currently being explored in the Aral Sea region as part of broader efforts aimed at combating desertification and restoring ecosystem functionality. Furthermore, studies conducted in other dried lake basins worldwide suggest that granulometric composition strongly influences ecological succession and reclamation success. Wang et al. (2020) reported that soils with balanced sand-clay ratios exhibit greater resilience to degradation and support faster vegetation recovery than extremely sandy substrates. These findings are particularly relevant for the Aralkum Desert, where soil texture

varies considerably across the landscape. Overall, the existing body of scientific literature demonstrates that the granulometric composition of soils formed on the dried Aral Sea bed is a key factor controlling their hydro-physical properties, salinization dynamics, susceptibility to wind erosion, biological productivity, and restoration potential. The heterogeneous distribution of sand, silt, and clay fractions throughout soil profiles reflects the complex interaction of marine sedimentation, aeolian processes, and pedogenic development. Therefore, a comprehensive understanding of soil texture is essential for developing scientifically sound strategies aimed at ecosystem restoration, phytomelioration, and sustainable land management within the Aral Sea region.

2. Materials and Methods

2.1. Study Area

The study was conducted on the dried bottom of the Aral Sea, located within the Aral Sea Basin of Central Asia. The investigated area represents a recently exposed seabed characterized by arid climatic conditions, high evapotranspiration rates, low annual precipitation, intensive aeolian activity, and widespread soil salinization. The climate of the region is sharply continental, with hot summers, cold winters, and annual precipitation generally ranging between 80 and 120 mm. Mean annual evaporation exceeds precipitation by more than 10–15 times, creating favorable conditions for salt accumulation and desertification processes. The parent materials of the studied soils consist primarily of marine sediments deposited during different stages of the Aral Sea's regression, subsequently modified by aeolian transport and redeposition processes. As a result, the soils exhibit considerable spatial and vertical heterogeneity in their physical and chemical properties.

2.2. Soil Sampling and Field Investigations

Field investigations were carried out following the guidelines of the FAO Guidelines for Soil Description (FAO, 2006) and the World Reference Base for Soil Resources (WRB, 2022). A representative soil profile was excavated in an area characterized by typical solonchak soils developed on the dried seabed. The soil profile was morphologically described according to standard international procedures, including:

horizon thickness and boundaries;
soil color (Munsell Soil Color Chart);
texture and structure;
consistency;
root distribution;
carbonate and salt accumulations;
visible morphological features associated with salinization processes.

Soil samples were collected from each genetic horizon at depths of 0–0.5, 0.5–27, 27–48, 48–64, 64–93, and 93–137 cm. Disturbed samples were transported to the laboratory for physical and granulometric analyses.

2.3. Particle-Size Distribution Analysis

The granulometric composition of soil samples was determined using the international standard pipette-sedimentation method based on the principles of Stokes’ Law, which is widely accepted in soil science research (Gee and Bauder, 1986; ISO 11277:2020).

Prior to analysis, soil samples were air-dried, gently crushed, and passed through a 1-mm sieve. Organic residues and soluble salts were removed where necessary to minimize analytical interference.

Particle-size fractions were separated into the following categories:

0.25 mm (coarse sand);
0.25–0.10 mm (medium sand);
0.10–0.05 mm (fine sand);
0.05–0.01 mm (coarse silt);
0.01–0.005 mm (medium silt);
0.005–0.001 mm (fine silt);
<0.001 mm (clay fraction).

The content of physical clay (<0.01 mm) was calculated as the sum of medium silt, fine silt, and clay fractions. Soil texture classes were assigned according to the classification system adopted by the former Soviet soil science school and correlated with USDA and WRB texture classes for international comparison.

2.4. Data Analysis

Descriptive statistical analysis was performed to evaluate the vertical distribution of granulometric fractions within the soil profile. Mean values, percentages, and depth-related trends were calculated for each particle-size fraction. The degree of profile differentiation was assessed using texture variation indices and vertical distribution coefficients. Changes in particle-size distribution with depth were interpreted in relation to sedimentological processes, marine depositional environments, and aeolian reworking following the desiccation of the Aral Sea. To evaluate ecological implications, relationships between particle-size composition and key soil functions were analyzed, including:

water infiltration capacity;
moisture retention potential;
susceptibility to wind erosion;
salt accumulation processes;
phytomelioration suitability.

Interpretation of soil physical behavior was based on established pedological and hydrological principles reported in international literature (Hillel, 2004; Brady & Weil, 2017).

2.5. Methodological Framework

The methodological framework of this study integrates field pedological observations, laboratory granulometric analyses, and ecological interpretation approaches widely applied in arid-land soil research. The study follows internationally recognized methodologies recommended by:

Food and Agriculture Organization (FAO);
World Reference Base for Soil Resources (WRB);
International Organization for Standardization (ISO 11277);
United States Department of Agriculture (USDA Soil Survey Manual).

This integrated approach allows reliable assessment of soil texture variability and its ecological significance within the newly formed soils of the Aralkum Desert.

2.6. Research Workflow

The research was conducted in the following sequence:
Selection of representative study sites on the dried Aral Sea bed;
Excavation and morphological description of soil profiles;
Collection of soil samples by genetic horizons;
Laboratory determination of particle-size distribution;
Calculation of physical clay content and texture classes;

Statistical evaluation of vertical texture variability;

Assessment of ecological and pedological implications;

Interpretation of results in the context of salinization, desertification, and ecosystem restoration processes.

Reliability and Quality Assurance

To ensure analytical accuracy and reproducibility, all laboratory measurements were performed according to internationally standardized procedures. Quality control included duplicate sample analyses, calibration of laboratory equipment, verification of sedimentation times, and comparison with certified reference materials where applicable. The adopted methodology provides a robust scientific basis for evaluating granulometric composition and its role in soil development and ecological restoration on the dried Aral Sea bed.

3. Results and Discussion

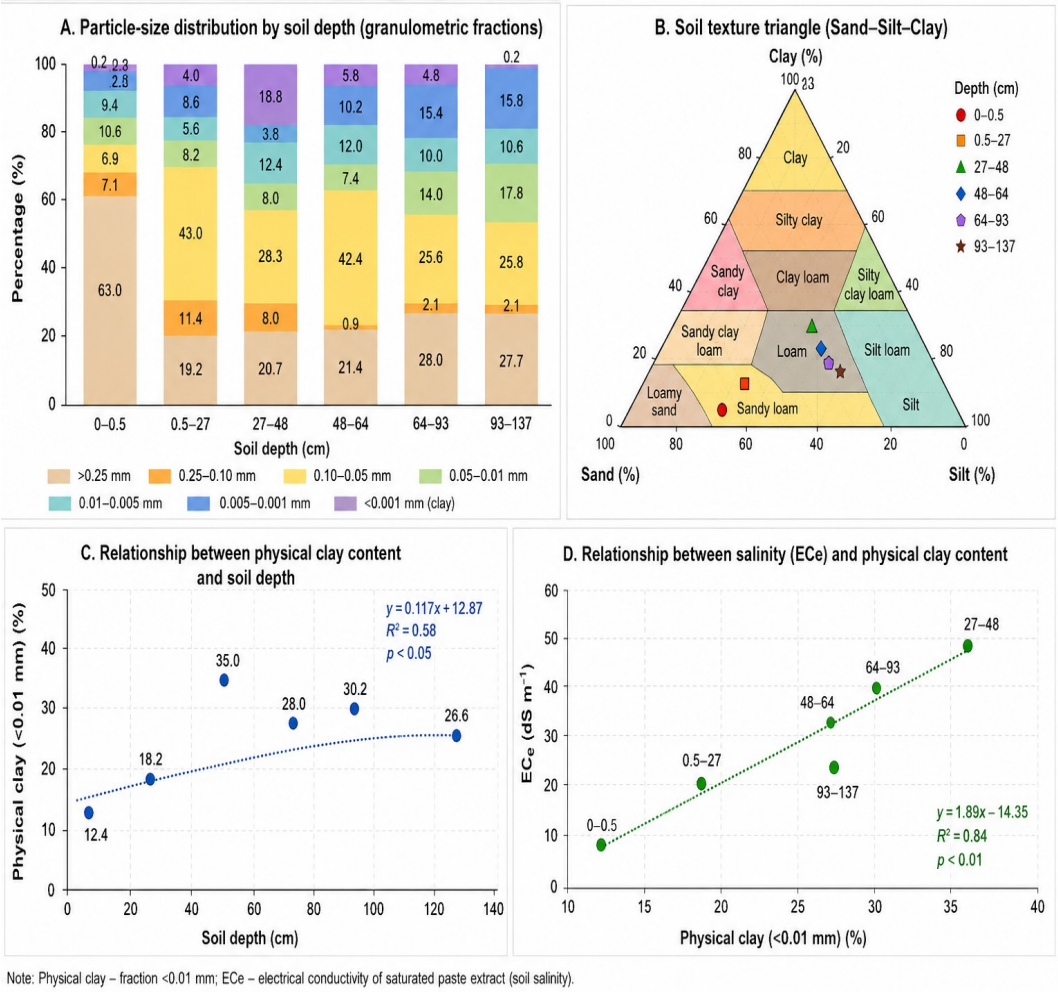
The particle-size distribution of typical solonchaks formed on the dried bottom of the Aral Sea revealed substantial vertical heterogeneity, reflecting the complex interaction between marine sedimentation, aeolian redistribution, and pedogenic transformation processes. Granulometric analysis showed that sandy fractions dominate throughout the soil profile, while the proportion of fine particles gradually increases with depth. Such textural differentiation is characteristic of recently exposed seabed environments where parent material stratification remains largely preserved and pedogenic processes are still at an early stage of development Table.1.

Table 1. Mechanical Composition of Typical Solonchaks Formed on the Dried Bottom of the Aral Sea

Depth interval, cm	Particle-size fractions (mm)								
	>0,25	0,25-0,1	0,1-0,05	0,05-0,01	0,01-0,005	0,005-0,001	<0,001	Physical clay (%)	Texture class
0-0,5	63,0	7,1	6,9	10,6	9,4	0,2	2,8	12,4	Sandy loam
0,5-27	19,2	11,4	43,0	8,2	5,6	8,6	4,0	18,2	Sandy loam
27-48	20,7	8,0	28,3	8,0	12,4	3,8	18,8	35,0	Medium loam
48-64	21,4	0,9	42,4	7,4	12,0	10,2	5,8	28,0	Light loam
64-93	28,0	2,1	25,6	14,0	10,0	15,4	4,8	30,2	Medium loam
93-137	27,7	2,1	25,8	17,8	10,6	15,8	0,2	26,6	Light loam

The surface horizon (0–0.5 cm) was characterized by an extremely high content of coarse sand particles (>0.25 mm), reaching 63.0%, whereas the physical clay content (<0.01 mm) was only 12.4%. This indicates a sandy-loam texture and suggests intensive aeolian sorting of sediments following desiccation of the Aral Sea. Similar findings were reported by Issanova et al. (2015), who demonstrated that wind erosion selectively removes finer particles from exposed seabed surfaces, resulting in enrichment of coarse fractions in the uppermost layers. The

predominance of coarse sand significantly increases soil permeability while reducing water-holding capacity, thereby creating unfavorable conditions for spontaneous vegetation establishment. The 0.5–27 cm horizon also exhibited a predominance of sandy particles, particularly the 0.1–0.05 mm fraction, which accounted for 43.0% of the soil mass. Although physical clay content increased to 18.2%, the horizon remained within the sandy-loam textural class. Such granulometric composition promotes rapid vertical water movement but limits moisture storage. Consequently, soil water is rapidly lost through deep percolation and evaporation, increasing susceptibility to drought stress and inhibiting biological productivity. According to Hillel (2004), sandy soils in arid regions often experience severe moisture deficits despite occasional water inputs, primarily because of their low field capacity and weak capillary retention. A notable textural discontinuity was observed in the 27–48 cm horizon, where physical clay content increased sharply to 35.0%, while the clay fraction (<0.001 mm) reached 18.8%. This horizon was classified as medium loam and likely represents a depositional layer formed during periods of lower hydrodynamic energy within the former marine basin. The enrichment of clay particles at this depth has important pedogenic implications. Fine-textured materials possess larger specific surface areas and higher cation exchange capacities, facilitating the retention of exchangeable sodium and soluble salts (Abrol et al., 1988). Therefore, this horizon may serve as a preferential zone for salt accumulation and secondary salinization processes. The 48–64 cm layer displayed a return to coarser sediment composition, with the 0.1–0.05 mm fraction accounting for 42.4% of total particles. Despite the dominance of sand fractions, physical clay content remained relatively high (28.0%), resulting in a light-loam texture.



Note: Physical clay – fraction <0.01 mm; ECe – electrical conductivity of saturated paste extract (soil salinity).

This alternation between coarse- and fine-textured layers indicates the polygenetic origin of the parent material and reflects repeated changes in depositional environments during the regression stages of the Aral Sea. Such lithological heterogeneity exerts strong control over vertical water flow and salt migration patterns. In the 64–93 cm horizon, physical clay content increased again to 30.2%, accompanied by a substantial proportion of fine silt particles (15.4%). The accumulation of these fractions enhances water retention, nutrient adsorption, and aggregate stability. Similar observations have been reported for saline soils of Central Asian drylands, where finer-textured horizons often exhibit greater fertility potential despite higher salt concentrations (Qadir et al., 2014). The presence of such horizons may therefore play a critical role in future ecological restoration efforts. The deepest investigated layer (93–137 cm) was characterized by a light-loam texture with 26.6% physical clay. Elevated proportions of medium and fine silt fractions indicate depositional heterogeneity associated with fluctuating hydrological conditions during different stages of sea regression. The irregular vertical distribution of particle-size fractions confirms that soil formation on the dried seabed remains strongly influenced by inherited sedimentological characteristics rather than fully developed pedogenic differentiation. Overall, the studied soil profile demonstrates a transition from sandy-loam textures in the surface horizons to light- and medium-loam textures in subsurface layers. Physical clay content varied from 12.4% to 35.0%, indicating considerable stratification of parent materials. This pattern is consistent with previous investigations conducted in the Aralkum Desert, where marine sediments and aeolian deposits jointly determine soil texture and profile morphology (Micklin, 2007; Issanova et al., 2015). From an ecological perspective, the dominance of sandy fractions in the upper horizons has significant implications for land degradation processes. Coarse-textured materials are highly vulnerable to deflation because they possess weak structural stability and low organic matter content. As a result, large quantities of salt-containing dust particles can be mobilized by wind and transported over long distances. Groll et al. (2016) estimated that tens of millions of tons of salt-dust aerosols are emitted annually from the dried Aral Sea bed, contributing to regional environmental degradation and adverse human health effects. The observed textural characteristics also directly influence the effectiveness of phytomelioration measures. Sandy and sandy-loam horizons favor the establishment of xerophytic and psammophytic vegetation such as Haloxylon aphyllum, Calligonum spp. and Salsola richteri. These species are capable of stabilizing loose sediments, reducing wind erosion, and enhancing soil organic matter accumulation. Meanwhile, loamy horizons provide improved moisture retention and nutrient availability, thereby increasing the probability of successful vegetation establishment and long-term ecosystem recovery. The results therefore indicate that soil texture is one of the primary factors governing hydro-physical behavior, salinity dynamics, ecological resilience, and reclamation potential of the dried Aral Sea bed soils. The coexistence of sandy surface layers and finer-textured subsurface horizons creates a complex pedo-ecological environment that requires site-specific management strategies. Future restoration programs should consider granulometric variability when selecting phytomeliorative species, designing reclamation measures, and assessing ecosystem recovery potential.The identified vertical differentiation of particle-size fractions demonstrates that the soils of the dried Aral Sea bed are still undergoing active pedogenic evolution. The predominance of sandy materials in surface horizons reflects ongoing aeolian reworking, whereas the accumulation of finer particles in subsurface layers preserves evidence of former marine depositional environments. Consequently, granulometric composition may serve as an important indicator for reconstructing

sedimentary history, predicting salinization patterns, and evaluating the long-term sustainability of ecological restoration initiatives in the Aralkum Desert.

CONCLUSION

The granulometric analysis of typical solonchaks formed on the dried bottom of the Aral Sea revealed significant vertical variability in particle-size distribution, reflecting the complex interaction of marine sedimentation, aeolian deposition, and ongoing pedogenic processes. The studied soil profile is predominantly characterized by sandy and sandy-loam materials in the upper horizons, whereas light-loam and medium-loam textures prevail in the subsurface layers. Physical clay content varied from 12.4% to 35.0%, indicating considerable lithological heterogeneity throughout the profile. The dominance of coarse sand fractions in the surface horizons confirms the strong influence of aeolian processes following the desiccation of the Aral Sea. The accumulation of coarse particles at the soil surface contributes to high permeability, low water-holding capacity, poor aggregate stability, and increased susceptibility to wind erosion. These characteristics explain the widespread occurrence of deflation processes and salt-dust storms that have become one of the major environmental challenges in the Aral Sea region. A gradual increase in fine particles, particularly physical clay and clay fractions, was observed in the deeper horizons. The enrichment of subsurface layers with fine-textured materials enhances moisture retention, cation exchange capacity, and nutrient adsorption potential. However, these horizons also create favorable conditions for the accumulation of soluble salts and exchangeable sodium, thereby contributing to the development and persistence of salinization processes. Consequently, soil texture exerts a dual influence on soil functioning by simultaneously improving water retention and increasing the risk of salt accumulation. The identified textural differentiation demonstrates that the soils of the dried Aral Sea bed are still at an early stage of pedogenic development and retain many characteristics inherited from their marine parent materials. The alternation of sandy and loamy horizons reflects changes in sedimentation regimes during different stages of sea regression and subsequent aeolian redistribution of sediments. Therefore, granulometric composition serves not only as an indicator of current soil properties but also as an important record of the geomorphological and environmental evolution of the Aralkum landscape. From an ecological perspective, the predominance of sandy materials in surface horizons limits natural revegetation and increases ecosystem vulnerability to degradation. In contrast, loamy subsurface horizons provide relatively favorable conditions for plant establishment and long-term ecosystem stabilization. These findings highlight the critical role of soil texture in determining vegetation succession, biological productivity, and restoration potential across the dried seabed. The results further demonstrate that granulometric composition is one of the key factors controlling hydro-physical properties, salinity dynamics, ecological resilience, and reclamation efficiency in the soils of the dried Aral Sea bed. Consequently, successful restoration and sustainable management of these landscapes require careful consideration of soil texture variability when selecting reclamation strategies and vegetation species. Based on the obtained findings, the establishment of drought- and salt-tolerant phytomeliorative species such as Haloxylon aphyllum, Calligonum spp., and Salsola richteri is recommended to enhance soil stabilization, reduce aeolian erosion, and promote ecological recovery. Furthermore, the application of organic amendments, biochar, and other soil conditioners may improve soil structure, increase moisture retention, and accelerate biological restoration processes. In summary, the granulometric composition of typical solonchaks on the dried Aral Sea bed constitutes a fundamental factor governing soil evolution, salinization processes, ecosystem functioning, and land restoration potential. The findings of this study provide

an important scientific basis for developing sustainable phytomelioration programs, mitigating land degradation, and supporting long-term ecological rehabilitation efforts in the Aral Sea region.

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